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Development of a low-cost attitude sensor for agricultural vehicles

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A B S T R A C T

The objective of this research was to develop a low-cost attitude sensor for agricultural vehicles. The attitude sensor was composed of three vibratory gyroscopes and two inclinometers. A sensor fusion algorithm was developed to estimate tilt angles (roll and pitch) by least-squares method. In the algorithm, the drift error of the gyroscopes was estimated using the inclinometers. In addition to tilt angles, the attitude sensor also estimated the absolute heading angle and position with inclination error correction by integrating a GPS. Tests were conducted on a flat field, a sloping ground and a bumpy road. Results showed that the attitude sensor was able to estimate the roll angle with the maximum root mean square error of 0.43°, the pitch angle with 0.61° and the heading angle with 0.64°. Moreover, the attitude sensor dramatically improved the positioning accuracy from 25.9 cm to 3.0 cm in the sloping ground test and from 8.4 cm to 3.7 cm in the bumpy road test. The proposed technology used in the attitude sensor will help to develop advanced agricultural applications.

1. Introduction

Considerable research has been reported recently on the application of Global Positioning System (GPS) for agricultural robots and precision farming. In the past, Real Time Kinematic Global Positioning System (RTK-GPS) and differential GPS (DGPS) technologies were so expensive that they had limited application in agriculture. But recently, GPS has become more affordable because of the invention of new technologies such as Virtual Reference Station RTK-GPS (VRS-RTK-GPS) that acquires correction signals via cell phone and DGPS that acquires differential correction signals from a satellite. In addition to vehicle location, vehicle attitude (roll, pitch and yaw angle) is also important for an autonomous vehicle and precision farming. While the cost for GPS units has been decreasing in recent years, expensive sensors like 3-axis fiber optical gyroscopes are still the mainstream technology for vehicle attitude sensing in most researches. Kise et al. (2001) developed a fully autonomous agricultural tractor using a 3-axis fiber optical gyroscope. Inoue et al. (2002) developed an autonomous tractor with a single axis fiber optical gyroscope. Instead of using fiber optical gyroscopes, other researchers reported on using four DGPSs to sense vehicle attitude (Bell, 2000; Elkaim et al., 1996; O’Connor et al., 1995, 1996). These approaches to vehicle attitude sensing are still not cost effective. Therefore, it is needed to develop a low-cost attitude sensor for agricultural vehicles.

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To measure the attitude of an off-road vehicle, quick response is required since most agricultural fields are uneven, generating random and rapid changes in the attitude of the vehicle. Mizushima et al. (2002) developed a method to sense tilt angles (roll and pitch) using a low-cost electrolytic fluid inclinometer. However, several issues have remained to be resolved, which include noisy response of the sensor and poor accuracy caused by the lateral acceleration of the vehicle. Moreover, the sensor was not able to operate in real time because of the need for noise correction.

This paper reports on the development of a low-cost attitude sensor composed of two inclinometers and three vibratory gyroscopes, which had quicker responses and higher signal to noise ratios compared with the inclinometers when used alone. A sensor fusion algorithm was designed to estimate roll and pitch angles by least-squares method, and the drift error of the gyroscopes was estimated using the inclinometers. In addition to tilt angles (roll and pitch), the attitude sensor also estimated an absolute heading angle and a position with inclination error corrections through a GPS. Field tests on a flat field, a sloping ground and a bumpy road were conducted to evaluate the accuracy of the developed attitude sensor.

2. Materials and methods

2.1. Prototype of low-cost attitude sensor

A prototype of the attitude sensor developed in this research is shown in Fig. 1. The sensor was composed of three gyroscopes (Gyrostar ENV-05F-03, Murata Manufacturing Co., Ltd., Japan) and
two inclinometers (D5R-L02-15, OMRON Co., Japan). As shown in Fig. 1, the gyroscopes are mounted onto the circuit board along the x, y, and z axes (roll, pitch and yaw). The inclinometers are mounted along the x and y axes (roll and pitch). The outputs of these sensors were acquired through a 16-bit analog/digital converter. The total cost of this attitude sensor was approximately $500 USD, only 1/20 of the cost of a conventional attitude sensor composed of fiber optical gyroscopes and accelerometers.

The Gyrostar is a relatively low-cost, small piezoelectric vibratory gyroscope developed for the automotive industry for use with a car navigation system. It consists of a triangular prism which is attached with the piezoelectric ceramic elements on each side. It has a linearity of $\pm 0.5\%$ at full scale and an angular velocity of up to $60^\circ/s$ with a resolution of $0.1^\circ/s$. However, the raw output from the gyroscope could not be used directly, because it suffers from drift over time and does not provide an absolute angle since the angle calculated from the gyroscope is a relative angle from the initial point. Therefore, the initial conditions must be inferred using an appropriate method to eliminate the drift error. To overcome these problems, two inclinometers based on electrolytic fluid sensors, coupled with a GPS unit, were used for drift elimination, the acquisition of initial conditions in roll/pitch measurement, and heading (yaw) estimation.

The two inclinometers were used to measure absolute inclinations and correct the drift error of the gyroscopes for roll and pitch angles. The device can provide global inclination angles. The concept of the sensor is based on a dielectric fluid with an air bubble inside a capacitive sensor. When the sensor is tilted, the bubble, moving under the force of gravity, changes the capacitance of the sensor elements. The inclinometer has a detecting range of $\pm 15^\circ$, and a scale factor of 100 mV for each degree of rotation. These performances would meet the requirements for agricultural vehicle application. This sensor has a delayed response with a time constant of 0.2 s and its step response time between $+15^\circ$ and $0^\circ$ is less than 2.5 s. Consequently, the signal-to-noise ratio (SNR) for the output of the sensor is low. This is acceptable because this sensor is primarily responsible for measuring absolute tilt angles and estimating the drift error of the gyroscopes, while the detection of rapid changes in the vehicle attitude is measured by the gyroscopes.

In addition to tilt angles (roll and pitch), the heading angle $\Psi_f$ and GPS position corrected for the error caused by the vehicle tilt are estimated. The system block diagram of the attitude sensor is shown in Fig. 2. Roll and pitch angles are estimated by the least-squares method (LSM) described in Section 2.2.1 using an angular rate of a gyroscope and an angle of an inclinometer. A heading angle is estimated by the least-squares method developed by Kise et al. (2001) using the angular rate of the gyroscopes and the position of the GPS. The GPS position error caused by the vehicle inclination is corrected using estimated roll, pitch and heading angles.

2.2. Attitude estimation

2.2.1. Roll and pitch estimations

Least-squares method (LSM) was applied to estimate the drift error of gyroscopes for roll and pitch inclinations. An estimated angular velocity $\omega_{Ek}$ at time $k$ is represented as follows:

$$\omega_{Ek} = \omega_{Gk} + d_k$$

where $\omega_{Gk}$ is the angular rate measured by the gyroscope at time $k$; and $d_k$ is the drift error of the gyroscope at time $k$. A squared error $\varepsilon_k$ at time $k$ is expressed as

$$\varepsilon_k = (\omega_{Ek} - \omega_{Tk})^2 = (\omega_{Gk} + d_k - \omega_{Tk})^2$$

where $\omega_{Tk}$ is the true angular rate. Applying the LSM to Eq. (2) gives

$$I_k = \sum_{i=k-M}^{k} (\omega_{Gi} + d_i - \omega_{Ti})^2$$

Fig. 1. Overview of a prototype of the attitude sensor.

Fig. 2. Schematic Diagram of the attitude sensor.
where $l_k$ is an error function of the LSM at time $k$; $M$ is the time span of the drift estimation assuming the drift error in this span is constant. Based on the LSM, the drift error $d_k$ at time $k$ is obtained by minimizing the error function $l_k$, i.e., $\partial l_k / \partial d_k = 0$, which is computed as follows:

$$d_k = \frac{\sum_{i=k-M}^{k} (\omega_{Gi} - \omega_{Ci})}{M + 1} = \frac{\sum_{i=k-M}^{k} \omega_{Gi} - \sum_{i=k-M}^{k} \omega_{Ci}}{M + 1} \tag{4}$$

In Eq. (4), it is assumed that the drift error $d_k$ is constant over the time interval $M \Delta t$ ($\Delta t$: sampling interval). The true inclination $\phi_{Ik}$ at time $k$ is expressed as

$$\phi_{Ik} = \phi_{Ik-1} + \phi_k + \delta_k \tag{5}$$

where $\phi_k$ is the inclination angle measured by the inclinometer; $\delta_k$ is the measurement error of the inclinometer, which is assumed to be white noise with zero mean. Then the true angular rate $\omega_{Ik}$ is

$$\omega_{Ik} = \frac{\phi_{Ik} - \phi_{Ik-1}}{\Delta t} \tag{6}$$

where $\Delta t$ is the sampling interval. Using Eqs. (5) and (6), $\sum_{i=k-M}^{k} \omega_{Gi}$ in Eq. (4) can be rewritten as follows:

$$\sum_{i=k-M}^{k} \omega_{Gi} = \sum_{i=k-M}^{k} \phi_{i} - \phi_{i-1} \Delta t = \sum_{i=k-M}^{k} \phi_{i} + \delta_i - \phi_{i-1} - \delta_{i-1} \Delta t \tag{7}$$

Because of the white noise with zero mean, we have $\sum_{i=k}^{k-M} \delta_i = 0$, and

$$\frac{1}{\Delta t} \left( \sum_{i=k-M}^{k} \delta_i - \sum_{i=k-M}^{k} \delta_{i-1} \right) = 0 \tag{8}$$

Eq. (7) can be rewritten, in view of Eq. (8), as follows:

$$\sum_{i=k-M}^{k} \omega_{Gi} = \sum_{i=k-M}^{k} \left( \phi_{i} - \phi_{i-1} \right) \Delta t = \sum_{i=k-M}^{k} \omega_{Gi} \tag{9}$$

where $\omega_{Gi}$ is the angular rate measured by the inclinometer. The drift error $d_k$ calculated in Eq. (4) is rewritten as follows:

$$d_k = \frac{\sum_{i=k-M}^{k} \omega_{Gi} - \sum_{i=k-M}^{k} \omega_{Ci}}{M + 1} \tag{10}$$

After considering the delayed response $n$ of the inclinometer, we finally obtain the following expression

$$d_k = \frac{\sum_{i=k-M}^{k} \omega_{Gi} - \sum_{i=k-M}^{k} \omega_{Ci} - n}{M + 1} \tag{11}$$

The final roll and pitch outputs from the attitude sensor are calculated as follows:

$$\phi_{Rk} = \phi_{R0} + \frac{\sum_{i=0}^{k} \omega_{Ri} \Delta t - \sum_{i=0}^{k} d_{Ri} \Delta t}{\sum_{i=0}^{k} \omega_{Ri} \Delta t} \tag{12}$$

$$\phi_{Pk} = \phi_{P0} + \frac{\sum_{i=0}^{k} \omega_{Pi} \Delta t - \sum_{i=0}^{k} d_{Pi} \Delta t}{\sum_{i=0}^{k} \omega_{Pi} \Delta t} \tag{13}$$

where $\phi_{Rk}$ and $\phi_{Pk}$ are roll and pitch outputs from the attitude sensor; $\phi_{R0}$ and $\phi_{P0}$ are the initial roll and pitch angles measured by the inclinometers; $\omega_{Ri}$ and $\omega_{Pi}$ are the angular roll and pitch rates measured by the gyroscopes; $d_{Ri}$ and $d_{Pi}$ are the estimated drift errors calculated by Eq. (11).
bottom of the antenna is about 10 cm. This error caused by the vehicle inclination can be corrected using the following equation;

\[
\begin{bmatrix}
X' \\
Y' \\
Z'
\end{bmatrix} = \begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} - E^{-1}(\phi, \theta_p, \theta_r) \cdot \begin{bmatrix}
a \\
b \\
h
\end{bmatrix}
\]

(20)

where \( \begin{bmatrix} X, Y, Z \end{bmatrix} \) is the corrected GPS position; \( \begin{bmatrix} X, Y, Z \end{bmatrix} \) is the position measured by the GPS; \( a, b, h \) is the 3D vector from the center of gravity of the vehicle to the GPS antenna position; \( \theta_\phi, \theta_\theta_p, \theta_\theta_r \) and \( \phi \) are the roll, pitch, and heading direction estimated by the attitude sensor respectively (Terao et al., 2001).

2.3. Field experiment

To evaluate the performance of the developed attitude sensor, field tests on a flat field, a sloping ground and a bumpy road were conducted. The flat field was a flat paved field, specially designed for testing agricultural vehicles. On the flat field, stability and reliability of the positioning, heading, and inclinations were evaluated for testing agricultural vehicles. On the flat field, stability and reliability of the positioning, heading, and inclinations were evaluated for testing agricultural vehicles. The flat field was a flat paved field, specially designed for testing agricultural vehicles. The flat field was a flat paved field, specially designed for testing agricultural vehicles. The flat field was a flat paved field, specially designed for testing agricultural vehicles.

### Results and discussion

#### 3.1. Flat field

On the flat field, the vehicle traveled along 15 m x 45 m rectangular lines. The results of the field tests are shown in Table 1. The accuracy was evaluated by calculating the root mean square error (r.m.s.) from the reference data (IMU and RTK-GPS). The errors of the raw gyroscopes and inclinometers are also listed in Table 1. The raw output from the gyroscopes had larger r.m.s. errors (12.5 (or 2.0 s) for roll and 12.1 (or 2.0 s) for pitch). These large errors were caused by the drift errors and the accumulated error at the end point for roll angle was 19 (or 5.33 /min) and for pitch was 16.7 (or 4.68 /min). Although the inclinometers were more accurate than the gyroscopes and did not have an accumulated error, the output had a delay and noise. On the other hand, the inclinations estimated by the LSM were improved dramatically. The r.m.s. error of the roll angle was 0.24 (or 0.24 s) and the pitch angle was 0.37 (or 0.37 s). Fig. 4 shows the comparison between the roll and pitch angles estimated by the LSM and the IMU on the flat field test. The estimated roll and pitch are free from the accumulated error of the gyroscopes and from the noise and delay of the inclinometers. The error was significantly higher at the start and stop points in the pitch estimation. This was caused by the measurement error of the inclinometer which senses the acceleration along the y axis and the LSM could not correct this error.

The absolute heading direction was estimated with an accuracy of 0.63 (or 0.63 s). The accuracy was improved dramatically from the raw output of the gyroscopes. However, the accuracy of heading estimation was low compared to the roll and pitch estimation, because the LSM for heading estimation was originally developed to estimate the drift error for a fiber optical gyroscope which has a smaller error than does a vibratory gyroscope.
The accuracy of position estimation was 6.5 cm r.m.s. error. Although the inclination correction was not very effective because of the flat surface, the accuracy of the position was improved by 20% compared to the position without inclination corrections (8.0 cm r.m.s. error).

3.2. Sloping ground

The vehicle started to travel with a level condition and then gradually inclined to the right more than 10° at the end of the sloping ground. The accumulated error of the gyroscope was 3.17° (2.17°/min) for roll and −12.03° (−8.22°/min) for pitch. The drift errors (°/min) of the gyroscopes vary depending on situations. The situations for the roll gyroscope were better than the situations for the flat field test, but the situations such as temperature changes for the pitch gyroscope happened to be worse. The r.m.s. error of the gyroscope was 2.33° for roll and 6.78° for pitch (Table 1). The r.m.s. errors of the gyroscopes were improved by 10.16° for roll and 5.29° for pitch compared to the flat field test. The improvement was due to a shorter time duration on the sloping ground since the space of the sloping ground was shorter than the flat field. For most cases, the longer the duration time is, the worse the r.m.s. error of the gyroscope will be. If the time duration is doubled, the accumulated error would be doubled if the drift errors (°/min) are the same. This explains why the r.m.s. error of the pitch gyroscope was improved even though the drift error (°/min) was higher than on the flat field. On the other hand, the accuracy of the inclinometers decreased compared to the test on the flat field (Table 1). This accuracy decrease was attributed to the unevenness of the ground surface. The surface for the sloping ground was rougher than the flat field and the vehicle wobbled throughout the test. As a result, the output signals from the inclinometer were noisy and had a time delay. Inclinations estimated by the LSM on the sloping ground are shown in Fig. 5. Both roll and pitch angles coincided with the reference values (IMU). The r.m.s. error of the roll was 0.23° and the pitch was 0.28°. These results confirmed that the developed attitude sensor can estimate inclinations accurately in relatively large sloping conditions by using the LSM.

The absolute heading direction was estimated with 0.64° r.m.s. error, while the raw output of the gyroscope for yaw angle was 3.51° r.m.s. error. The accuracy was almost the same as that for the flat field. Again, the accuracy of the heading estimation was lower than the roll and pitch estimation. However, this accuracy should be sufficient for inclination correction of the GPS position described below.

Fig. 6 shows the comparison between the error of estimated position with inclination corrections and that of the raw GPS position for the sloping ground. Both position errors were within 10 cm for the travel distances between 0 m and 25 m since the ground was relatively level (the roll angle was less than 2°). The error of the raw GPS position increased to 40 cm due to the large roll inclination (12°) after the travel distance exceeded 25 m. As a result, the r.m.s. error of the raw GPS position was 25.9 cm. On the other hand, the error of the position with inclination corrections was less
than ±10 cm and the r.m.s. error was 3.0 cm, which was approximately 10% of the raw GPS position error. This result indicates that the estimated roll, pitch and heading direction were accurate and inclination corrections were effective in reducing the position error caused by the inclination of a sloping ground of more than 10°.

3.3. Bumpy road

The accumulated error of the gyroscope was 7.86° for roll and −11.13° for pitch for the bumpy road. The r.m.s. errors of the gyroscopes (4.54° for roll and 6.25° for pitch) were almost the same as those for the sloping ground. Meanwhile, the r.m.s. errors of the inclinometers (3.28° for roll and 1.84° for pitch) were dramatically reduced compared to the flat field and sloping ground, even though the accumulated error was not measured. These results indicate that due to its slow response, an inclinometer does not work well in a field condition where the attitude changes rapidly and frequently. On the other hand, the LSM estimated roll and pitch angles accurately; the r.m.s. error of the roll angle was 0.43°, and the pitch angle was 0.61° (Table 1). The result of the roll and pitch angles estimated by the LSM is shown in Fig. 7.

Fig. 8 presents the temporal response of the heading angle obtained by the gyroscope, estimated heading, and IMU. At the end of the 50 s experiment, the difference between the raw output of the gyroscope and the IMU had been accumulated up to 13°. Meanwhile, the estimated heading was consistent with the IMU data, and the accumulated error was less than ±2° with the r.m.s. error of 0.59°.

Temporal changes in the estimated position error and the raw GPS position error are illustrated in Fig. 9. The raw GPS position error included a constant offset bias of about −5 cm and the oscillation range was ±10 cm with 8.4 cm r.m.s. error. In contrast, the estimated position fell within ±5 cm with the accuracy of 3.7 cm.

Fig. 10. Power spectral density for the bumpy road test: (a) roll angle; and (b) pitch angle.
r.m.s. error. This result shows that inclination correction for the estimated attitudes greatly improved the position accuracy and could be applied for agricultural vehicles running in uneven fields or on bumpy roads.

The roll and pitch power spectral density on the bumpy road was calculated using the IMU output (Fig. 10). As shown in Fig. 10, the oscillation frequency of the vehicle for the roll and pitch was observed for up to 2 Hz. This frequency range would be expected for normal agricultural operations.

The accuracy of the attitude sensor on the various field conditions was evaluated and the results showed that the estimation algorithm for the low-cost attitude sensor effectively improved the attitude estimates of agricultural vehicles for normal agricultural operations (i.e., the angle range of ±12° and the vehicle vibration frequency of up to 2 Hz). However, quantitative performance evaluation of agricultural vehicle applications (e.g., autonomous tractors) is yet to be done. This may involve the comparison of autonomous guidance accuracy with the attitude sensor and the IMU.

The attitude sensor developed in this research will be useful for vision-based precision farming systems (Sugiura et al., 2005; Kise and Zhang, 2008), in which the pixel position in the image coordinate system needs to be transformed to the global coordinates (latitude and longitude) to generate geographic information system (GIS) maps for making better management decisions. This transformation would require an attitude sensor to detect the vehicle attitude since the location where the camera is pointing at is defined by the camera mount angle (tilt, roll and pan) and the attitude of the vehicle (roll, pitch, heading and GPS position).

4. Conclusions

A low-cost attitude sensor composed of three vibratory gyroscopes and two inclinometers was developed. A least-squares method was proposed to estimate the drift error of gyroscopes, and it was able to estimate the roll angle with the maximum root mean square error of 0.43° and the pitch angle with 0.61°. In addition to roll and pitch angles, an absolute heading direction was estimated using the gyroscope for a yaw angle and a GPS. The maximum r.m.s. error of the heading direction was 0.64°. Using estimated roll, pitch and heading direction, the inclination correction of the GPS position was implemented, which greatly improved the position accuracy from 25.9 cm to 3.0 cm r.m.s. error on the sloping ground and from 8.4 cm to 3.7 cm on the bumpy road. The estimation algorithm for the low-cost attitude sensor effectively improved the attitude estimates of agricultural vehicles in normal agricultural operations (the angle range of ±12° and the vehicle vibration frequency of up to 2 Hz). The proposed technology used in the attitude sensor will help to develop advanced agricultural applications.

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